

Intelligent Propulsion System Foundation Technology

Summary of Research

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Program Objectives and Structure

The purpose of this cooperative agreement was to develop a foundation of intelligent propulsion technologies for NASA and industry that will have an impact on safety, noise, emissions and cost. These intelligent engine technologies included sensors, electronics, communications, control logic, actuators, and smart materials and structures. Furthermore this cooperative agreement helped prepare future graduates to develop the revolutionary intelligent propulsion technologies that will be needed to ensure pre-eminence of the U.S. aerospace industry.

The program consisted of three primary research areas (and associated work elements at Ohio universities): 1.0 Turbine Engine Prognostics, 2.0 Active Controls for Emissions and Noise Reduction, and 3.0 Active Structural Controls.

Significant Accomplishments

1.0 Turbine Engine Prognostics

Disk Life Meter – Diffusion, Creep Deformation, Hot Corrosion & Quench Cracking (OSU)

Investigation of the diffusion and creep deformation mechanisms in a newly developed superalloy identified several distinct deformation mechanisms, which are highly dependent upon microstructure, temperature, and stress. A creep deformation map illustrating the observed deformation mechanisms as a function of stress and temperature was developed. Microtwinning was found to be the dominant deformation mechanism in the samples crept at 1250°F (677°C) at a stress level of 100ksi (690MPa). The deformation mechanisms observed in the samples crept in the 1300°F (704°C) temperature regime at varying levels of stress showed mixed deformation modes operative. A combination of isolated faulting of the γ' precipitates and continuous faulting of both the γ' precipitates and matrix were observed along with matrix dislocation activity. At the higher temperature regime 1400°F (760°C), stacking fault ribbons and an increased amount of matrix dislocation activity, which correlates with the thermally activated climb/bypass deformation mode were observed. The dissolution of the tertiary γ' precipitates were observed, which may have dictated the change in deformation mechanism from isolated precipitate shearing events to climb/bypass.

The hot corrosion morphology revealed by laboratory tests were in good agreement with the service experience of aircraft engine disks, which is characterized by localized corrosion, in the form of pits. Tests at 1200°F revealed no hot corrosion because the salt was solid at the test temperature lower than its eutectic point of 1216°F, while the tests at 1400°F resulted in severe hot corrosion.

Quantitative analyses of quench cracking during heat treatment of both elastic and plastic tensile behavior in the range of 1850°F to 2050°F, including measures of strain rate sensitivity and strain hardening, have yielded constitutive relations which provide good agreement between modeling efforts and experimental observations.

Malfunction and Operator Error (OSU)

A number of different research activities were conducted, including a review of PSM incidents, PSM accidents, and a comparative review of existing propulsion system interfaces. These different activities complemented each other and provided converging lines of evidence concerning cognitive systems issues related to the handling of propulsion system malfunctions. Several cognitive activities were identified that need to be carried out by the flight crew, and potentially supported by the automation, both prior to and during a PSM event. These include: monitoring, detection, diagnosis, and action selection.

2.0 Active Controls for Emissions and Noise Reduction

Intelligent Combustor – WSR, Shock Tube & TAPS (UD)

A Well Stirred Reactor was designed, fabricated, and assembled with the following specifications:

- Operating pressure = 1-20 atm.
- Air flow rates: 2.0 lbm/sec
- Fuel flow rate: 0.2 lbm/sec
- Residence Time = 2-8 ms
- equivalence ratio = 0.3-2.5
- Fuels: Jet A, JP-8, heptane and decane.

A 50—bars shock tube with the following specifications was designed, fabricated, assembled, and tested:

- Operating pressure = 50 atm.
- Temperature: 500-3000C
- Residence Time = 0.1 to 8 ms
- Fuels: Jet A, JP-8, heptane and decane.

A 20-atm. TAPS (twin-annular, pre-swirl) combustor test facility was designed and adapted to the AFRL high pressure combustor research facility in Dayton, OH.

Intelligent Combustor - Active Combustion Control/MEMS (CWRU)

A MEMS microvalve for fuel modulation was designed and fabricated which exhibited an actuation scheme combining such attributes as large displacement, moderate force and high frequency operation. The microvalve is comprised of four individual silicon wafers that are bonded together. Fabrication was accomplished using a combination of resources: the MicroFabrication Laboratory (MFL) at CWRU and the MEMS Exchange.

A micromachined flow sensor integrable with the microvalve was developed to enhance valve performance and enable closed-loop control. A high-temperature double-sampling amplifier (HTDSA) test chip was designed and laid out. It was fabricated through MOSIS using the AMI 1.5-um bulk CMOS process. The test chip includes a complete high-temperature sensor interface circuit, consisting of a correlated double sampling amplifier with delta modulator, a temperature-stabilized oscillator, a Wheatstone bridge stimulus generator, and a fully-differential operational amplifier (FDOA) test circuit.

SiC thin films were developed to improve the reliability of the flow sensor and the valve in the harsh gas turbine environment. Test data collected include Young's Modulus, film stress, stress gradient, fatigue strength and abrasion resistance.

Intelligent Combustor Control – TAPS/LBO/Lean Flammability Limits (UC)

Tests of the TAPS fuel nozzle in the atmospheric rig were conducted to study fuel injector dynamics, LBO, and emissions at atmospheric pressure. A new TAPS nozzle adaptable to atmospheric combustion was designed, fabricated and tested. Pressure pulsations and heat release characteristics were mapped in a wide range of equivalence ratios and air flow rate. Testing was performed for different pilot/cyclone splits to determine effects on LBO limit. Particular attention was devoted to the behavior near the lean flammability limit. It was found that there is a rise in both dynamic combustion pressure and CO concentrations before LBO. New emissions diagnostics equipment was purchased, installed and initial tests were performed.

Active combustion control tests were conducted in the atmospheric rig. Several high frequency valves were characterized in a wide range of frequencies of >1000Hz. Combustion dynamics were characterized at different equivalence ratios and near Lean Blow Out (LBO). Pressure and light emission signatures were analyzed and effectiveness of control by fuel split modifications and by modulations of fuel in the pilot and main circuits between pilot and main was determined. Studies were conducted on damping effects of fuel tubes on pulsations in fuel flow rate.

A pressure vessel for a high pressure rig was designed and fabricated, and the design of air, fuel supply and control, air heating, air cooling and water cooling systems, and ignition system were finished.

Intelligent Combustor – Spray Characterization (UC)

A fundamental study was conducted on atomization properties of liquid jets to improve current understanding of governing atomization physics. In addition, data on the mode and positions of liquid breakup, spray coverage area and spray properties over a wide range of test conditions (momentum ratios, Weber numbers and Reynolds numbers) were obtained to assist in the design of fuel/air premixers. Experiments were conducted on liquid jets injected normally into a uniform subsonic crossflow and on spray properties at the exit plane of twin-annular pre-swirl (TAPS) premixers.

A correlation of the jet penetrations was developed for jet breakup at a constant streamwise location using Digitizeit! and a nonlinear regression routine NLREG.

Three primary sets of experiments were completed to characterize the fuel dispersion characteristics of the TAPS premixers. First, the mode and location of the liquid jet breakup within the premixer were recorded at various operating conditions employing a borescope imaging system. Second, the resulting spray exiting the premixer was studied via a planar Mie-scattering probe. High resolution photographs and videos were recorded to determine dispersion characteristics and to identify under which conditions wall impingement occur. Lastly, a two-

dimensional PDPA system was employed to quantify the atomization produced by the circumferential jets around the exterior of the nozzle body.

Active Noise Reduction – Plasma Injection (OSU)

Research was conducted in two areas: (1) to develop high amplitude and bandwidth actuators capable of forcing high-speed and high Reynolds number jets for noise mitigation and (2) to utilize the developed actuators for noise mitigation in high subsonic and supersonic jets. One of the key components of the system, a high voltage (~ kHz) and current (~ amp) plasma power supply and control system that can power a multitude of actuators simultaneously with prescribed phase pattern among the actuators and with a frequency up to 200 kHz, could be acquired commercially. The design and fabrication of such an eight-channel power supply and control system was conducted.

Preliminary results were obtained using this power supply and control system driving the plasma actuators. This DC plasma actuator power supply and control system is composed of two high voltage and three low voltage DC power supplies, eight high voltage transistor switches, and a PC based function generator. The fabrication of this highly flexible, repetitively pulsed, multi-channel high voltage plasma power supply and control system was very recently completed. The system is able to produce high voltage and current pulses between up to 8 pairs of pin electrodes located in a high-speed flow (localized arc plasma actuators). The repetition rate, the duty cycle, and the phase of the pulses can be independently controlled for every channel. Capabilities of the system included demonstration of phase-locked images of a Mach 1.3 ideally expanded axisymmetric jet at five different phases. The jet is forced with 8 actuators and operating at 10 kHz and all 8 in phase. The effect of forcing organizes the structures of the jet and makes them very robust and semi-periodic - similar to those of a very low speed and Reynolds number jet.

Active Noise Reduction – Fluidic Injection, Shape Memory Alloys & Acoustic Liners (UC)

Subscale experimental testing of fluidic injection as a means of attenuating jet noise by injecting small jets of air into the fan and core stream flows was performed on a scale model of a typical regional jet engine. New hardware was designed to integrate fluidic injection capabilities for both the core and fan streams within the existing hardware. This new hardware included nozzles and hardware to pipe air internally to the nozzle exit planes. Results showed that:

a) the fan fluidic injection was more effective than core injection. The noise attenuation on the core stream due to core injection was diminished once the fan stream reached approximately 400 ft/sec. Since typical fan flow velocities are in the area of 1000 ft/sec, not much acoustic benefit was gained with core injection.

b) fan injection proved to be much more effective at reducing the peak noise levels. As the injection pressure was increased, the peak noise levels continued to drop, but tube noise continued to rise as a consequence. There appeared to be a linear relationship between the peak noise reduction and injection pressure.

c) fluidic injection was more successful at reducing jet noise at higher engine power settings. In almost every configuration, the fluidic injection did little to reduce jet noise at low engine power settings and even raised EPNL levels in some cases.

Full scale testing was conducted on an existing closed-circuit wind tunnel modified to open the circuit after the contraction. The test section was replaced with a constant area duct of 24x24 inch cross section. The outflow of this constant area duct is then a free jet of nearly room temperature air at uniform velocities up to Mach 0.2. This jet was used to simulate the free stream over an engine nacelle at take-off velocity. A second duct was manufactured to simulate

the fan flow and was fitted to the bottom of the 24x24 inch duct. It was fed by a high pressure air system and generated a free jet of nearly constant velocity up to Mach 0.6. This second duct is five inches high, representing the full-scale height of a typical separate flow fan nozzle outlet. The flow emergent from this duct was used to simulate the fan flow of a separate flow engine at take-off power. The results of the full-scale tests were encouraging and demonstrated an effect of fluidic injection on the flow field. Experimental issues were identified which would be helpful in guiding further research in this area.

Experiments were conducted on the potential use of Shape Memory Alloys (SMA) for jet noise reduction applications in the exhaust nozzle.. SMA is a material that can deform when the temperature rises above a specific value, and then resume the original shape when the temperature drops below that value. A significant disadvantage of many passive reduction techniques is the increased drag penalty. The potential to use SMA in such a way that passive noise reduction techniques, such as chevrons or tabs, are "turned on" when required for jet noise reduction, and "turned off" when no longer required was evaluated. The tests did not use actual SMA material in the nozzle configurations, but rather simulated the deformed, or noise reducing configuration by connecting the chevron edges with a wire and gluing it in place. Far-field acoustic measurements were obtained in order to assess the expected noise penalty of the wire compared to the benefit of the chevrons. Initial results were quite promising. The wire significantly reduced jet noise below that of the chevron nozzle at all angles and frequencies. Based on these promising initial results, a relatively comprehensive optimization process was completed. Three different diameters of wire were tested at four different locations. It is interesting to note that the reductions for this technique are similar to those for fluidic injection. The configuration was not successful when used in coaxial flow. It is suspected that the portion of the wire that interacted with the fan stream was the source of the additional noise. However, scavenging air from the compressor or other storage means is not required.

Work was conducted on the design and fabrication of a flow duct liner test facility. The purpose of the flow duct facility was to test panels of acoustic liners under the conditions of high speed grazing flow and high intensity sound that are typically experienced in the nacelle of aircraft engines. Capabilities include test panel sizes of 5 inches wide by 24 inches long, 6 Hartman generators covering the range of 1000 Hz to 4000 Hz, and electro-magnetic compression drivers for acoustic excitation.

Acoustic impedance experiments on new liner concepts were conducted in an existing wave tube apparatus that was developed under a previous research project sponsored by NASA. The wave tube is of 1.5 inch by 1.5 inch square cross section. A total of 16 acoustic transducers were employed to measure the acoustic field in the tube. The apparatus was designed to perform the following two types of acoustic measurements 1) Normalized Acoustic Impedance of a single layer acoustic liner consisting of a cavity and a porous face sheet. In this measurement the plane waves impact the test sample at right angles to the porous face sheet and 2) Acoustic Attenuation or Suppression (Δ dB) by a 4.5 inch long liner panel. Acoustic Impedance Tests were conducted on samples of single layer liners with the following types of face sheets:

- Metallic perforated sheets
- Smart Memory Alloy simulation
- Perforated flexible membranes

The SMA simulation with rigid perforated sheets showed that the variation of acoustic resistance with the porosity was the same as that for the base line perforated sheets with circular holes. For a given porosity, the flexible membranes produced very small resistance compared to the baseline metallic perforated face sheets.

3.0 Active Structural Controls

Turbine Cooling Control – Unstable Profile Prediction, Enhanced HT, Tech Demo (UC)

A LINUX cluster and 3D unsteady computer simulations of a gas turbine high pressure nozzle and rotor were performed with purge cavities to assess the impact of unsteadiness on turbine temperature profiles. The nozzle and rotor were gridded with the multiblock grid generation system and source terms applied to represent the film cooling. There were 56 blocks with 1.5 million cells in the nozzle grid, and 97 blocks with 1.8 million cells in the rotor grid. Initial steady runs were accomplished using a computational program with 18 processors in the LINUX cluster for the nozzle and rotor. The Mach number and Total Temperature in the nozzle were determined. The Mach contours showed the shock emanating off the trailing edge and the Total Temperature contours clearly showed the cooling flow. A relative Mach number was determined to show where the strong rotor shocks are evident at midspan. The Relative Total Temperature in the rotor was calculated, and streamlines were spawned in the purge cavity showing the complex flowfield that exists there.

Simulations, both in 2- and 3-D, were made on the effects of a pulsed cooling flow on a steady cross flow. The simulations were conducted with three goals in mind; first to investigate the fluid mechanics of a pulsed cooling flow, secondly to adaptively "cancel out" the cross flow unsteadiness that would be caused by rotor-wake interactions, and lastly, as a result of the adaptive cooling, to determine if a reduction in the amount of cooling flow use was possible. The 2- and 3-D grids were generated using the commercially available grid generation software package, Gambit, from Fluent. With Gambit, a structured 2-D mesh was created with a cooling channel oriented at 30° to the main channel. The commercially available solver CFD++, by Metacomp Technologies, Inc., was employed to run the simulations in a two-step process. For the steady, or first portion, of the simulation the simulation was run for 2000 iterations with CFL numbers varying from 1 to 250 over the first 500 iterations. The lessons learned from the 2-Dimensional cases were then applied to a 3-D grid. The same injection angle, from the 2-D case, was used with the 3-D simulation. The geometry of the cooling hole, however, was a slot. The grid was again structured and consisted of 1,533,667 grid points and 1,479,200 elements. The major difference between the 2- and 3D grids is the change in the injection angle from 30 to 45 degrees. This was done to simplify the modeling process.

A computational model was created of the unsteady flow passing over a turbine blade caused by the wake of the upstream rotor row, combined with steady cooling flow that illustrates the effects of an unsteady crossflow on a steady cooling flow. A multi-step approach was taken to model the unsteady rotor wake flow. The first step was to model the turbine blade as a flat plate experiencing crossflow with one cooling hole and several different injection angles; first in two dimensions and steady flow to establish the basic flow field and establish a baseline for comparison. Once the baseline was established the next step was to vary the crossflow for the flat plate with varied injection angles and see the effect on the steady flow of one cooling jet. Several different methods were used for varying the crossflow, including time varied mass flow and external sinusoidal pulsing. Grids were generated with Gambit for a two-dimensional flat plate with cooling hole injection angles of 15°, 30°, 45°, 60°, and 90° to be used on this work element and the work element with a steady crossflow and pulsed cooling jet. Starting with the 15° and 30° cases baseline steady analysis was done using CFD++ as the flow solver. For the baseline cases the crossflow was modeled as a steady reservoir temperature and pressure at the inflow and a set back pressure at the outflow. With the baseline flow established the next step was trying out various inflow conditions within the CFD++ solver to model the unsteady crossflow. The first method used a time varied mass flow condition where a time step and maximum mass flow were set. Then the amount of variance for the mass flow was set and the mass flow was

ramped up and down in accordance with the given time step. With the changing mass flow and fixed back-pressure flow transient reversal occurred.

Work was conducted on three-dimensional simulations of an unloaded cooled vane under various operating conditions. Such conditions include a range of blowing ratios (0.4-2.0) as well as cross flow turbulence intensity levels (1, 10 and 20%). These simulations were compared and evaluated to better understand cooling jet physics and their effects on the cooling properties of this particular vane design. These cases were run at Mach number 0.23 and Reynolds number based on hydraulic diameter of 1.4×10^5 with a main flow total temperature of 705.6K° and a cooling flow total temperature of 360K° . Contours of film cooling effectiveness, total temperature and total pressure along with detailed streamline maps showing the propagation of cooling flows through the passage were used to compare each case. The vane design chosen incorporates a circular leading edge with two staggered rows of nine cooling holes, followed by a flat side which has one row of thirteen holes located 0.5 inch downstream of the leading edge. A fine grid was generated that incorporated the entire design geometry. Three rows of cooling holes were simulated for a total of 31 cooling holes. The flow through each hole and the feed plenum were simulated. This grid consists of 14 million cells and has y^+ values of 20 in the holes and 0.5-2.0 along the channel walls. The next step taken was to elevate the cross flow turbulence levels to values that are more in line with that produced in an operating gas turbine. Two turbulence levels of 10% and 20% were chosen. One simulation with increased cross flow turbulence intensity was completed. Simulations for the full geometry of an unloaded cooled vane used in an experimental rig test section have been conducted for several blowing ratios at free stream turbulence intensities of 1, 10 and 20%.

To explore active turbine blade film cooling control through pulsed injection, a Combustion Wind Tunnel Facility (CWTF) and a generic vane blade were utilized. The CWTF is capable of temperatures nearing 1400°F , Mach numbers of approximately 0.30, and velocities in excess of 600 ft/s. The vane blade allows for both showerhead film cooling and sidewall film cooling. The blade was designed to allow separate control to each set of film cooling holes. The air entered through the base of the blade into two separate chambers and exited through the various film cooling holes. The blade was instrumented with static pressure taps to measure the blade surface static pressure. The blade surface temperature results were determined for the various freestream conditions and varying individually for both the showerhead and sidewall blowing ratios. It was evident that the most effective cooling takes place when both the showerhead and sidewall cooling are used simultaneously. At all blowing ratios for these cases, the blade surface temperature was kept the lowest. When only sidewall film cooling is used, the front surface of the blade was the hottest temperature, which would be expected. For showerhead film cooling, these holes are angled towards the floor of the facility and it is evident that they do cool the lower half of the blade and not the upper half as would be expected.

Turbine Cooling Control – Combustor Simulator (OSU)

Two combustor simulators of different sizes were designed and constructed to obtain detailed three-dimensional heat transfer information in a controlled laboratory environment as close to actual gas turbine engine operation as possible. These simulators are capable of producing an arbitrary number of hot streaks of sufficiently significant temperature profile to be representative of the engine. The devices were designed and constructed to avoid non-uniform blockage within the flow path and to be sufficiently rigid that foreign material does not become dislodged and passed through the turbine stage. In addition to the design, construction and demonstration of the heater technology, all of the hardware necessary to locate the combustor simulators in a gas turbine rig has been designed.

Shape Changing Airfoil (OSU)

Research was conducted on the feasibility of a high-strength and lightweight structural material that can be utilized in a shape-changing airfoil design. The strength and stability characteristics that a novel Aluminum alloy would have to attain in order to meet the demands outlined for potential low-temperature stage fan blades were defined at the outset of the project: a) achieve a room-temperature strength of 620MPa while maintaining sufficient stability to exceed 450MPa at 150°C, b) exceed 10% ductility over the range of in-service temperatures, and c) demonstrate an exceptional resistance to aging in order to maximize component life.

The main thrust of the development of this new alloy was grounded in the principle of rapid solidification. Several alternate approaches to alloying and processing were evaluated. In order to gain a more thorough understanding of the role of Mn additions in pinning the extremely fine grain size that naturally occurs in the rapidly quenched flakes, three binary alloys were cast at levels that exceed what would be feasible to cast using conventional methods (1.0wt%, 1.5wt%, and 2.0wt%) due to the extensive eutectic formation that would occur during solidification. As expected, the flakes contained very little if any eutectic constituent volume fraction based on direct SEM observation.

Flake was consolidated in copper tubes and then rolled after stripping the copper away. TEM observation of the Al-Mn binary alloys was carried out on samples that had been subjected to extended times at elevated temperatures (between 350 and 500°C) in order to gain a better understanding of the degree to which the refined grain structure of the consolidated flake could be maintained at temperatures well beyond the expected maximum operational temperature exposure of 150°C. The distribution of Al₆Mn and the performance of the particle dispersion in locking down the grain structure was demonstrated to varying degrees of success even at extreme temperatures (400°C for 81 hours), with the 2wt% Mn binary alloy demonstrating the most positive contribution to stability. A modeling approach to estimate and compare alloy residual alloy strength as a function of temperature was developed using mechanism recovery algorithms of a) Recovery/Coursening, b) Dislocation Release/Flow and c) Dislocation Refinement. The resulting model correctly predicted pure metal creep and is being adapted to engineering materials.

Smart Containment System (UA)

The general objective of this research was to investigate possible scenarios of crack propagation in a composite softwall containment system due to forces produced by the unbalanced fan after the blade out event in the engine. The particular objective of this study was to apply a force-moment system to the front flange of the containment in a dynamic and static way in order to propagate the crack from the initial hole.

In the first step of the investigation, the blade-out was simulated to produce a realistic hole in the containment. Results of the simulation were also used to assess the loading produced by the interaction of the unbalanced fan with the undamaged section of the containment system. It was found that the containment can be subjected to twisting, shearing and bending forces and moments.

The post impact loading conditions were studied parametrically using LsDyna3D for a dynamic case and ABAQUS implicit code for a static load application. In each case, the energy stored in the inner housing and stresses in elements of highest stress concentration were measured. LsDyna3D simulations demonstrated crack initiation and propagation for the applied moments. It was observed that the crack path depended on the type of elements used and the density of the mesh used in the simulation.

Publications

1. X. Yu, S. Garverick, "G_m-Stabilized, High-Temperature Switched-Capacitor Circuits in Bulk CMOS", **IEEE Intl. Solid-State Circuits Conference**, to be held in February 2005 in San Francisco
2. S. C. Stouffer, D. R. Ballal, J. Zelina, D. T. Shouse, R. D. Hancock, and H. C. Mongia (2005), "Development and Combustion Performance of a High-Pressure WSR and TAPS Combustor," **AIAA Paper No. 2005-1416**, to be presented at the 43rd AIAA Aerospace Sciences Meeting, Reno, NV.
3. S. S. Sidhu, J. L. Graham, D. R. Ballal, and H. C. Mongia (2005), "Investigation of Heptane Combustion at 50-atm. Using a Shock Tube," **AIAA Paper No. 2005-1447**, to be presented at the 43rd AIAA Aerospace Sciences Meeting, Reno, NV.
4. S. Tambe, "Liquid Jets In Subsonic Crossflows", **MS Thesis, University of Cincinnati**, Dec 2004
5. S. Tambe, S-M Jeng, H. Mongia, and G. Hsiao, "Liquid Jets In Subsonic Crossflows", **AIAA Paper No. 2005- 24141**, to be presented at the 43rd AIAA Aerospace Sciences Meeting, Reno, NV.
6. C. Haldeman, R. Mathison and M. Dunn, "Design, Construction, and Operation of a Combustor Emulator for Short-Duration High-Pressure Turbine Experiments", **AIAA Paper No. 2004-3829**
7. X. Zheng, R.K. Goldberg, W.K. Binienda, and G.D. Roberts, "Development and Implementation of Rate Dependent Composite Material Model for Shell Element Application in LSDYNA", pp 633-641 in **Earth and Space Engineering Construction, and Operations in Challenging Environments**, edited by R.B. Malla and A. Maji, ASCE, 2004.
8. J. Ratzlaff, P. Orkwis, and S. Balu, "A Numerical Study of 3D Turbulent Cooling Jet Interaction over a Range of Blowing Ratios", **ASME GT-2005-68796**, Reno, Nevada, June 2005.

Inventions

1. "High-Temperature Architecture and Electronics for Internal Combustion Control" Inventors: Steven L. Garverick (Case); Xinyu Yu (Case) Task No.: Work Element 2.1 Active Combustion Control
2. "Piezoelectrically Actuated Large Displacement Microvalve for High Flow, High Differential Pressure, Harsh Environment Applications" Inventors: Mehran Mehregany (Case); Srihari Rajgopal (Case); Aaron Knobloch (GE); Jeffrey Fortin (GE); Christian Zorman (Case) Task No.: Work Element 2.1 Active Combustion Control